Searches for 0νββ decay with bolometric detectors

Giovanni Benato
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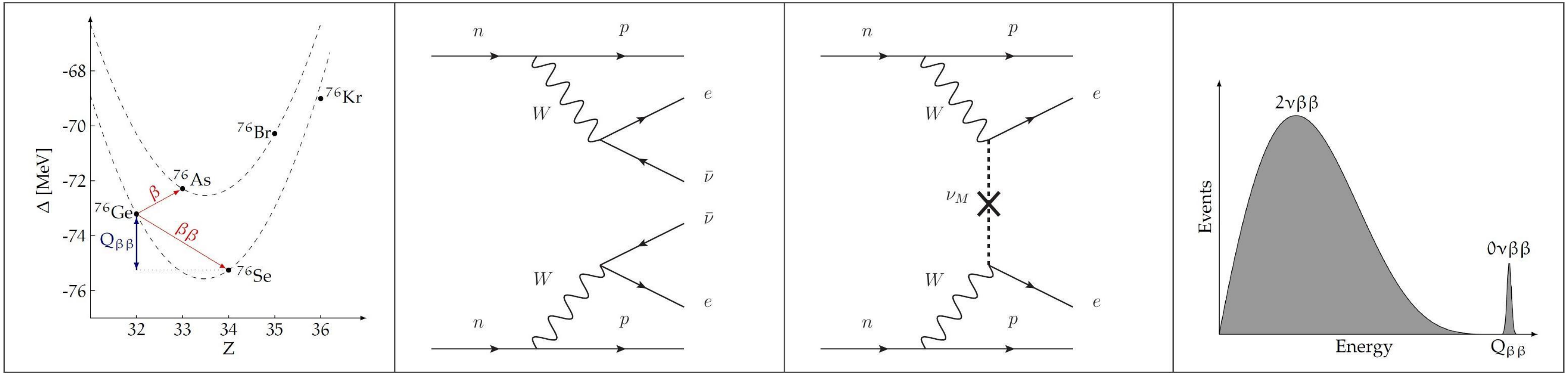
0νββ decay



ββ decay signature

- Continuum for 2νββ decay
- Peak at $Q_{\beta\beta}$ for 0νββ
  →Only necessary and sufficient signature!
- Additional signatures from event topology, pulse-shape discrimination, multi-channel readout, daughter tagging, …

0νββ rate

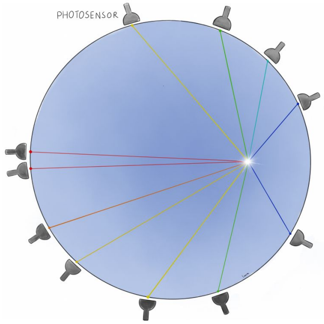
$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2/m_e^{\,2}$$

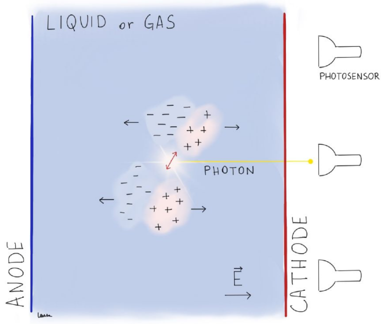
- $T_{1/2}^{0\nu\beta\beta}$ = 0νββ halflife
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element
- f = new physics term

Experimental fauna

Liquid scintillators

- High efficiency
- Easily scalable
- Poor resolution
- KAMLAND-Zen, SNO+



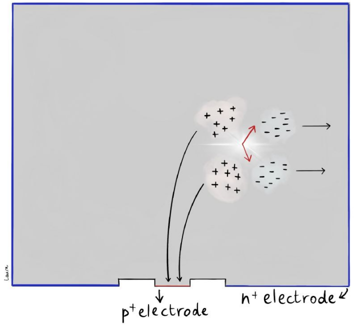


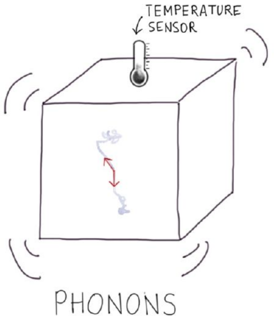
Time Projection Chambers

- Event Topology
- Enriched/depleted runs
- Multiple isotopes
- nEXO, NEXT, PandaX-III, LZ, DARWIN

Germanium detectors

- Excellent energy resolution and background
- Granularity
- Single isotope
- LEGEND, CDEX

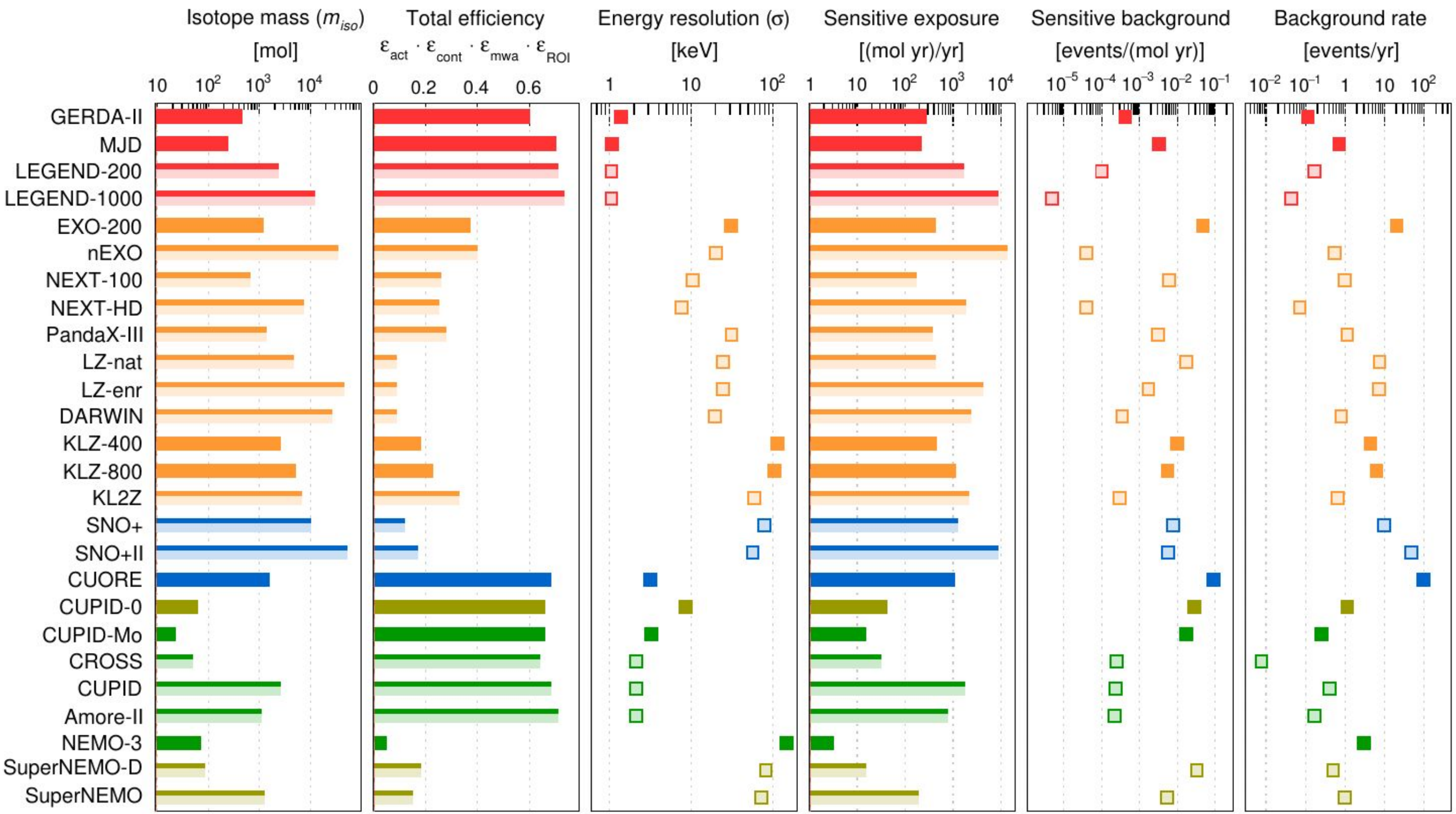




Bolometric detectors

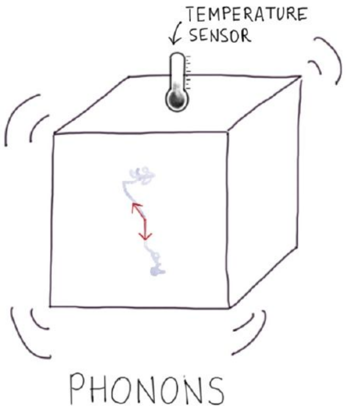
- Excellent energy resolution
- Multiple isotopes
- Granularity
- CUORE, CUPID family, AMoRE

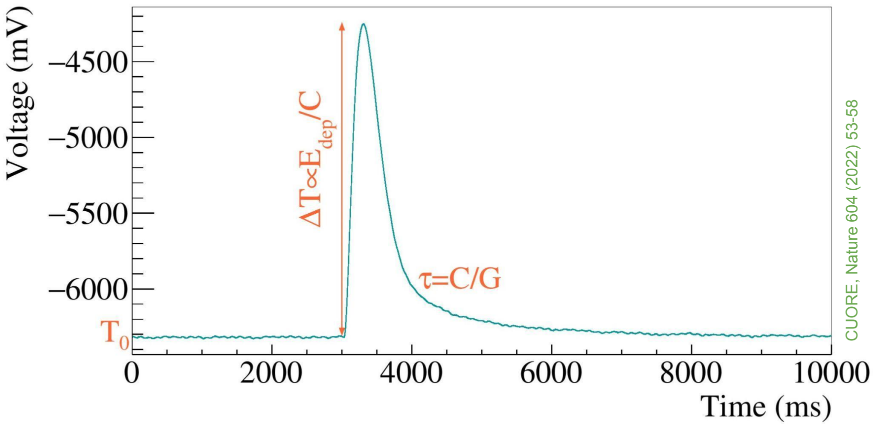
Experimental fauna



Bolometric detectors

- Crystal absorber coupled to phonon or temperature sensor
  →ΔT ∝ # of phonons ∝ deposited energy
- ΔT of the order of 0.1 mK
  →must be operated at 10-30 mK
- Slow response (from μs to s)
- Many materials suitable as an absorber
  →can study 0νββ decay on multiple isotopes
- Energy resolution in [5,20] keV range
  →in most cases, dominated by thermal noise and a yet unidentified energy-dependent term
- No dead layer
  →sensitive to surface contamination of surrounding passive materials

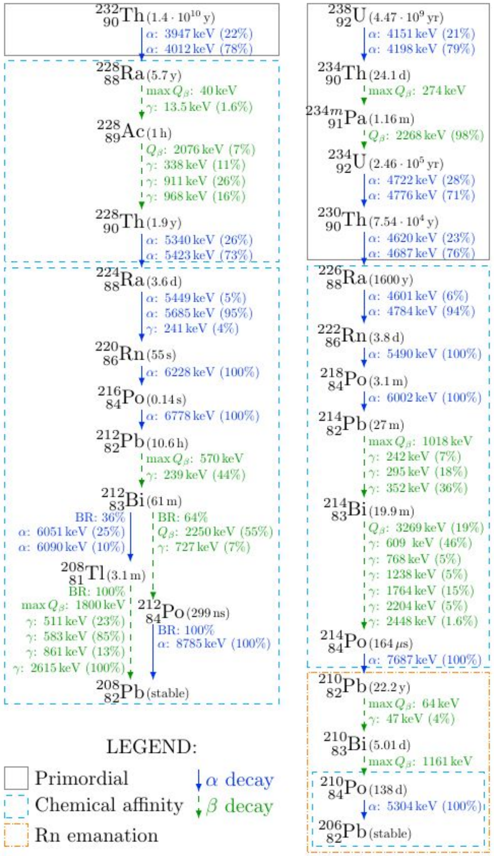




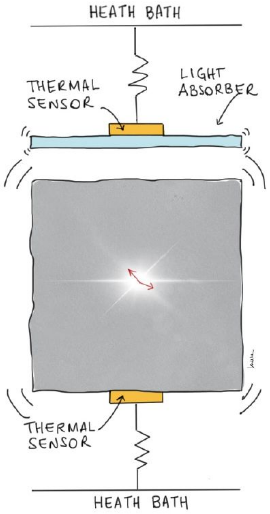
CUORE, Nature 604 (2022) 53-58

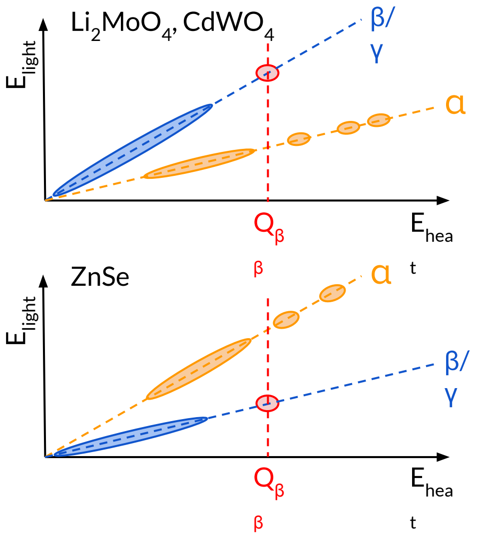
Backgrounds

- Cosmic rays
  →Go underground, and install a muon veto
- **^{238}U and ^{232}Th** contamination in detector and passive materials
  →Strict protocols of material selection and cleaning
  →Massive Pb and Cu shielding against external γ's
  →Particle identification to actively suppress α background
  →Time-dependent analysis to identify subsequent events from the same decay chain
- Neutrons
  →Passive shielding
- Anthropogenic radioactivity
  →Usually not so worrisome
- Pileup of 2νββ decay events
  → Affects only crystals with ^{100}Mo due to large decay rate



Scintillating bolometers



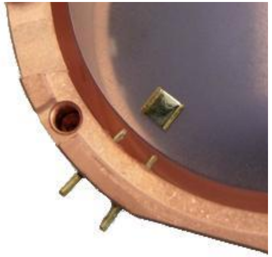


- Scintillation process depends on density of energy deposition and hence on particle type
  →LY dependence
  →Time profile dependence
- Dual readout technique necessary for next-generation experiments
  →Heat for optimal energy resolution
  →Scintillation for particle discrimination
- Detection of scintillation light performed with secondary bolometer
  →Ge or Si crystal wafer instrumented with thermal sensor
- Light detector cannot touch the main absorber to avoid thermal cross-talk
  →Light collection sub-optimal

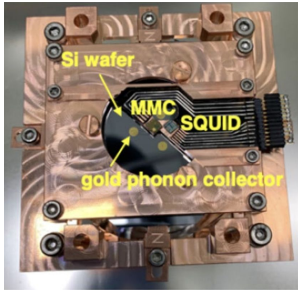
Phonon readout technologies

Neutron-Transmutation-Doped Ge thermistors

- Neutron-doped Ge chips
- Slow response time (>ms)
- Huge dynamic range
- Easy mass production
- Affordable for heat and light
- Applicable to any absorber

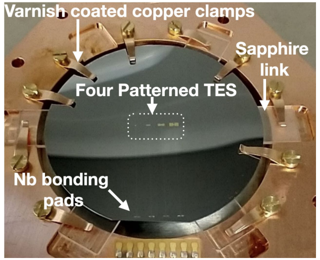


Metallic Magnetic Calorimeters

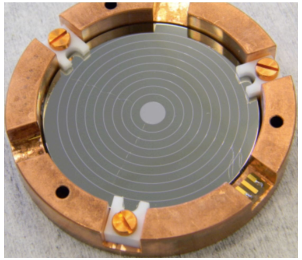


- Metallic paramagnetic sensor transducing temperature rise into a magnetic flux change
- Read-out with SQUID
- Fast (μs)
- Large dynamic range + good resolution

Transition Edge Sensors



- Fast response time (μs)
- Great for low-threshold measurements
- Small dynamic range
- Difficult mass production
- Not directly applicable to all crystals

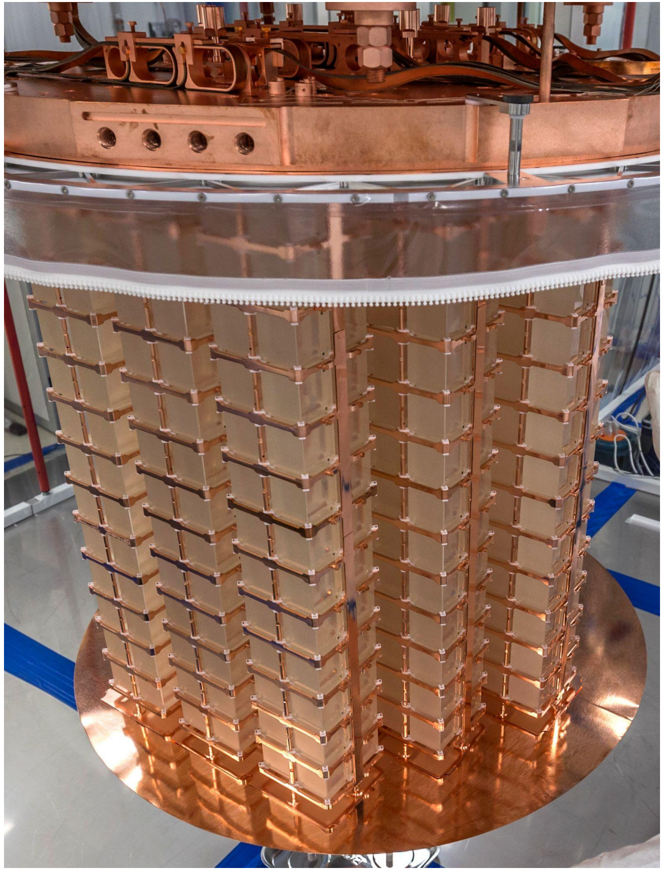


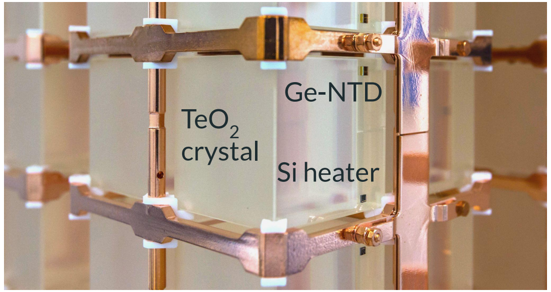
Neganov Trofimov Luke amplification

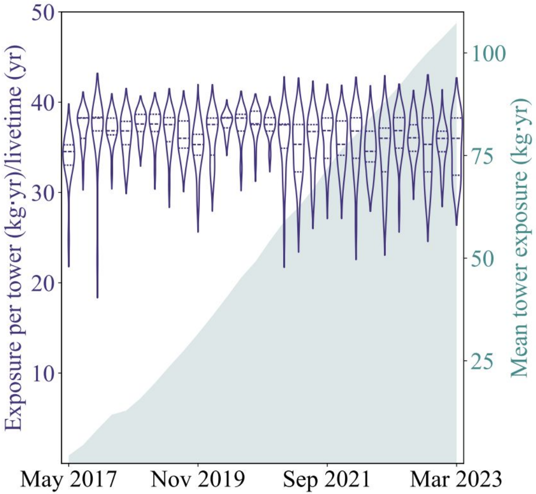
- Create E-field in semiconductor crystal to drift electron-hole pairs
- Phonon emission by e-h pairs
- Well demonstrated with NTDs

CUORE

- Located at LNGS, Italy
- 988 TeO_2 crystals
  → 742 kg of detector mass
  → 206 kg of isotope
  →No particle discrimination
- Natural abundance (34%)
- Passive Pb and borated PE shieldings
- Largest dilution refrigerator ever operated
- Stable operation singe 2019
- Accumulated exposure > 2 ton·yr

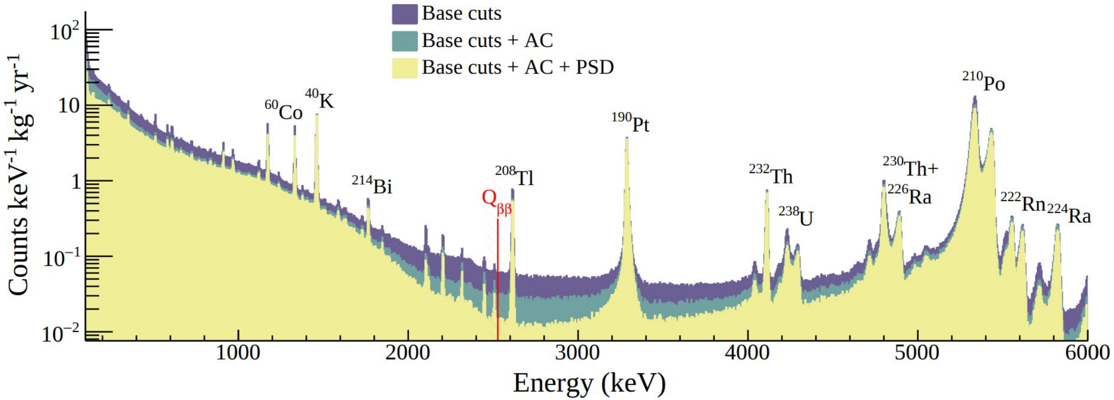


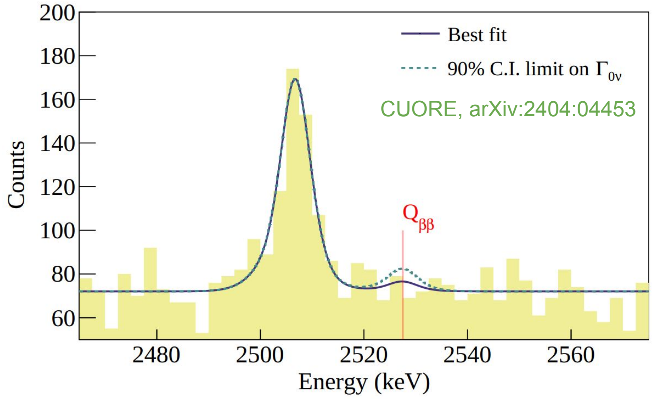




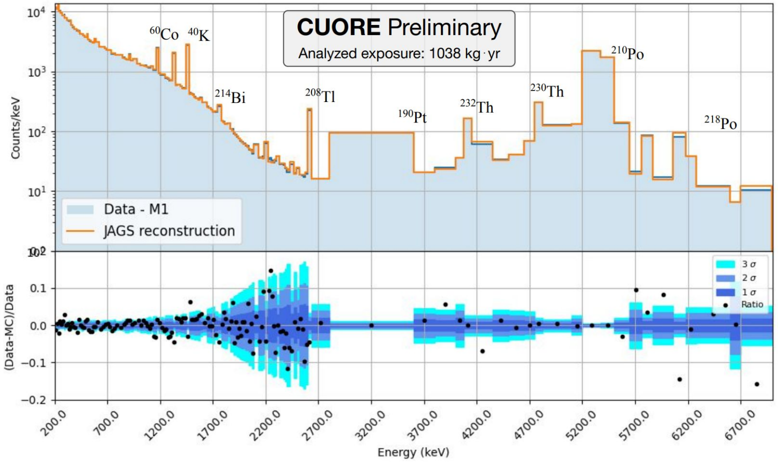
CUORE, Nature 604 (2022) 53-58
CUORE, arXiv:2404:04453

CUORE

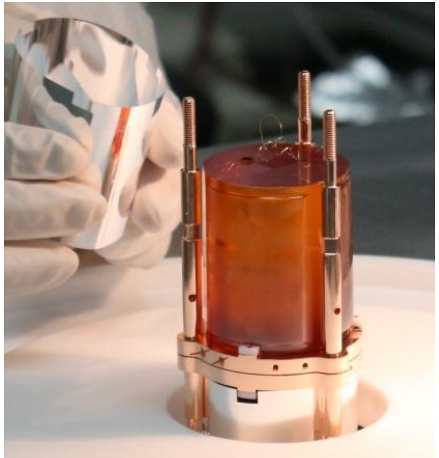




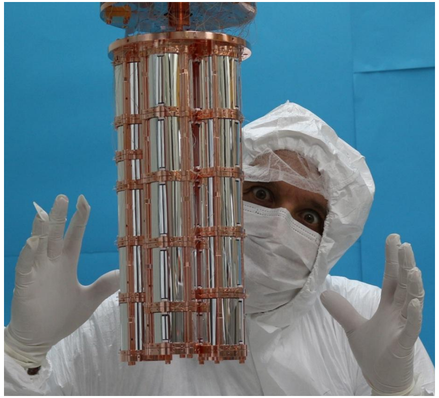
- $T_{1/2}^{0\nu\beta\beta}(^{130}Te) > 3.8 \cdot 10^{25}$ **years @ 90% c.i.**
- Background index: $(1.42 \pm 0.02) \cdot 10^{-2}$ counts/keV/kg/yr
- $T_{1/2}^{2\nu\beta\beta} = 7.71^{+0.08}_{-0.06}(stat)^{+0.12}_{-0.15}(syst) \cdot 10^{20}$ yr
- Comprehensive background model explaining in detail the origin of all spectral features
  →Fundamental for the optimization of CUPID
  →Dominated by degraded α particles from copper

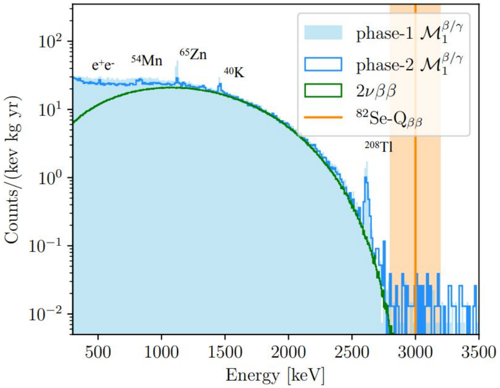


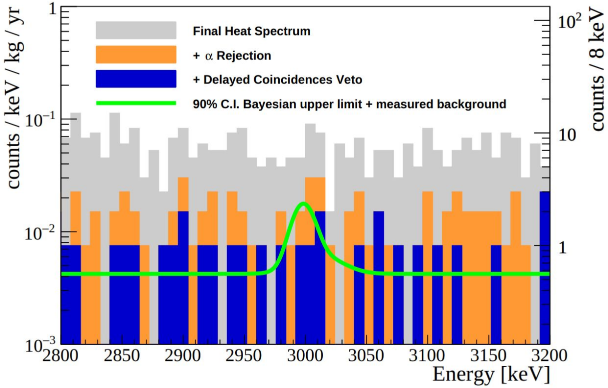
CUPID-0



- 26 **ZnSe** crystals (24 enriched at 95% in ^{82}Se)
- Light detectors: Ge wafers + NTDs
  →Particle discrimination through pulse shape of light signal
- Phase I with reflector foil to maximize light collection: 9.95 kg·yr
- Phase II without reflector foil: 5.74 kg·yr
- Energy resolution ~22 keV FWHM
- **$T_{1/2}^{0\nu\beta\beta}(^{82}Se) > 4.6\cdot10^{24}$ yr @ 90% c.i.**
- $T_{1/2}^{2\nu\beta\beta}(^{82}Se) > [8.69 \pm 0.05(stat)^{+0.09}_{-0.06}(syst)]\cdot10^{24}$ yr

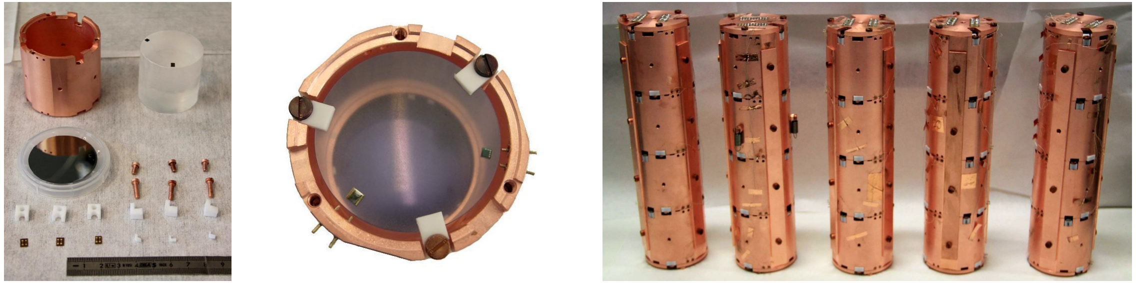


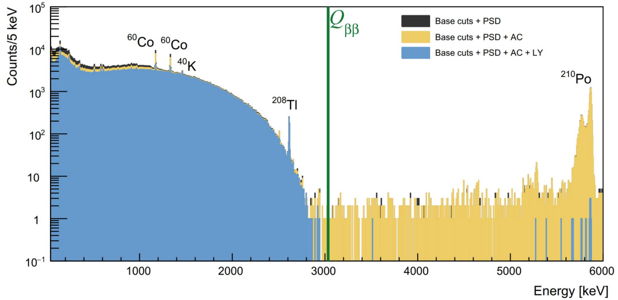


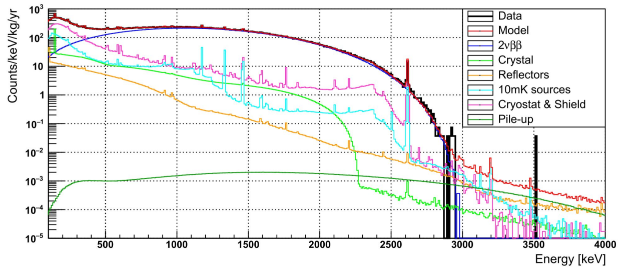


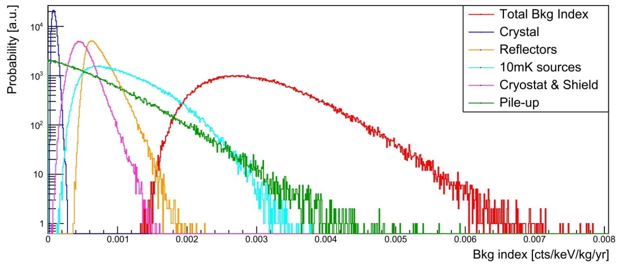
CUPID-Mo

- 20 Li_2MoO_4 crystals enriched at 97% in ^{100}Mo
- 20 Ge wafers instrumented as light detectors
- Total exposure: 2.16 kg·yr
- **$T_{1/2}^{0\nu\beta\beta}$ > 1.8·10^{24} yr @ 90% c.i.**
- $T_{1/2}^{2\nu\beta\beta}$ = [7.07 ± 0.02 (stat.) ± 0.11 (syst.)] · 10^{18} yr
- Comprehensive background model yielding fundamental information for the design of CUPID
  →Background index:
  $[2.7^{+0.7}_{-0.6}(stat)^{+1.1}_{-0.5}(syst)] \cdot 10^{-3}$ counts/keV/kg/year

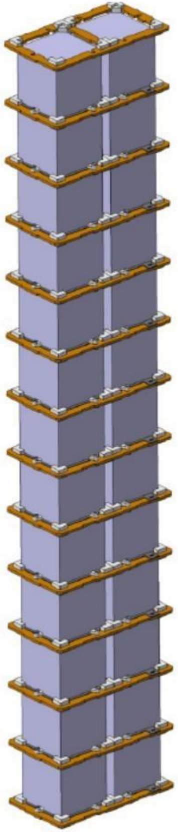


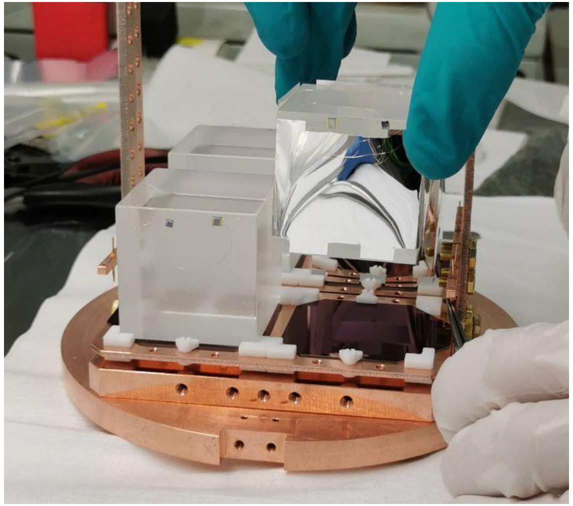


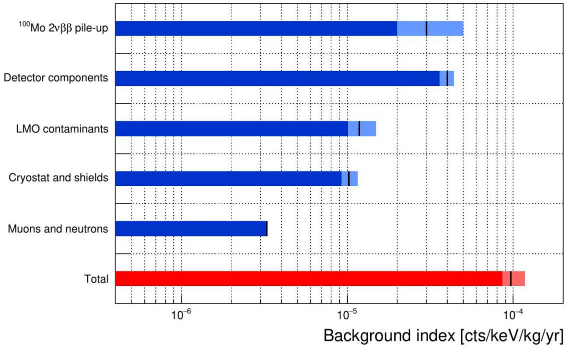




CUPID



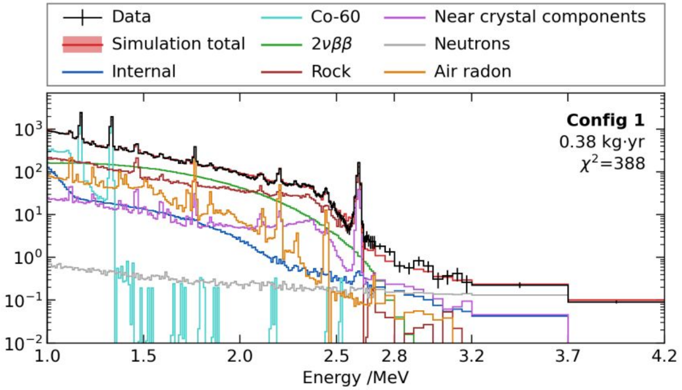


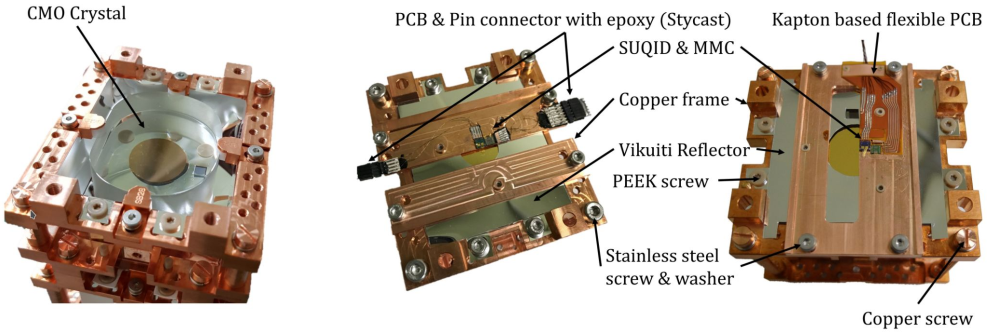


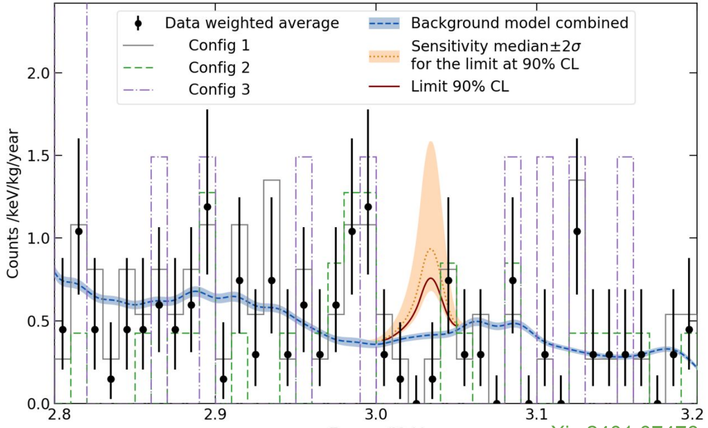
- $Li_2{}^{100}MoO_4$ crystals for 240 kg of ^{100}Mo
- To be installed in CUORE cryostat
- Ge light detectors with Neganov-Trofimov-Luke amplification to enhance signal-to-noise ratio
  →Reject α particles and 2νββ pile-up events
- Expected background: 10^{-4} counts/keV/kg/yr
- Expected energy resolution: 5 keV
- Discovery sensitivity: $T_{1/2}^{0\nu\beta\beta} = 10^{27}$ yr
  →Cover inverted-ordering region

AMoRE

- Various Mo-based crystals read-out with MMCs
- AMoRE-pilot: 1.9 kg of $^{48depl}Ca^{100}MoO_4$ @ YangYang
  →Background ~0.5 counts/keV/kg/yr
- AMoRE-I: 4.6 kg of $^{48depl}Ca^{100}MoO_4$ + 1.6 kg of $Li_2{}^{100}MoO_4$ with improved muon veto and passive shielding
  →Background reduced by an order of magnitude
- AMoRE-II: 100 kg of ^{100}Mo in new cryostat @ Yemilab
  →Background goal 10^{-4} counts/keV/kg/yr
  →Sensitivity $T_{1/2}^{0\nu\beta\beta}$ ~ 10^{27} yr





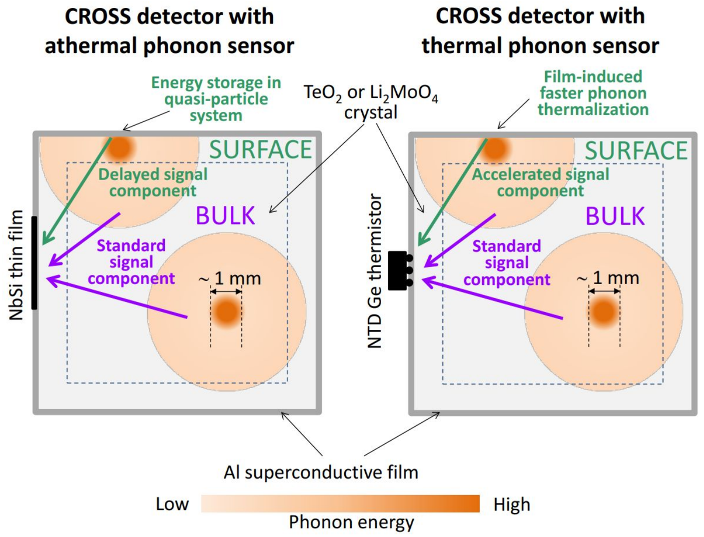


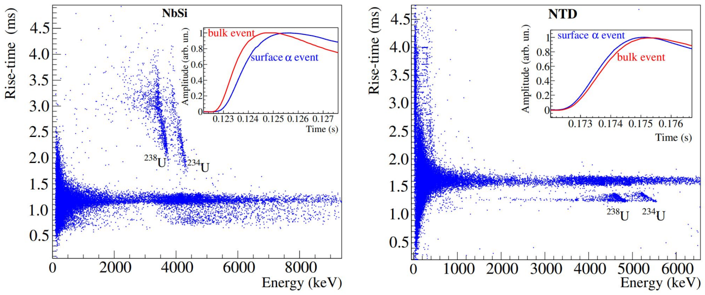
arXiv:2401:07476

How to go beyond next-generation

- Discriminate single β's from passive materials from ββ events occurring in the crystal bulk
  →Discriminate surface vs bulk event
- Identify external γ rays
  →Active shielding
- New isotopes with high Q-value

CROSS

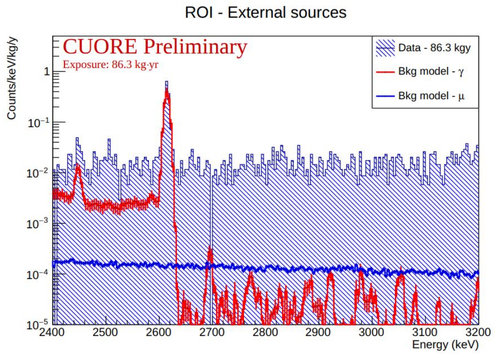


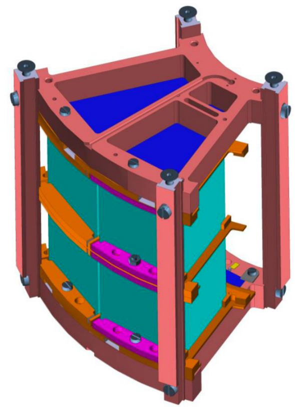


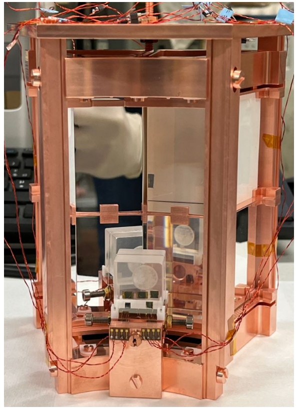
- Main idea: coat crystal surfaces to enable bulk-vs-surface discrimination via pulse shape analysis
  →Allow to suppress both α and β particles
  →Could be applied to non-scintillating crystals
- Bonus idea: add light detector with Neganov-Trofimov-Luke (NTL) amplification to enhance signal-to-noise ratio
- R&D measurements @Canfranc demonstrated performance of surface-vs-bulk discrimination both with NTDs and NbSi thin-film sensors
  →Scalability to large crystals to be proved
- NTL amplification demonstrated to be scalable
  →Adopted by CUPID

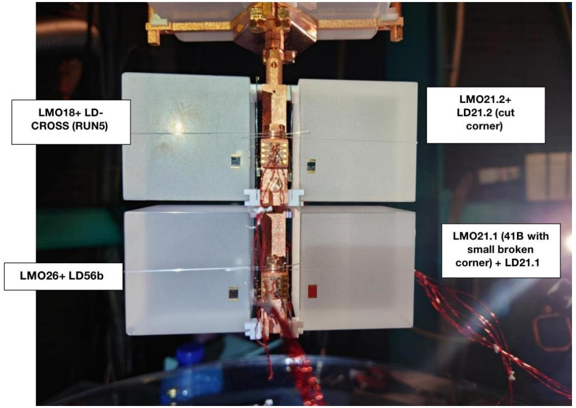
BINGO

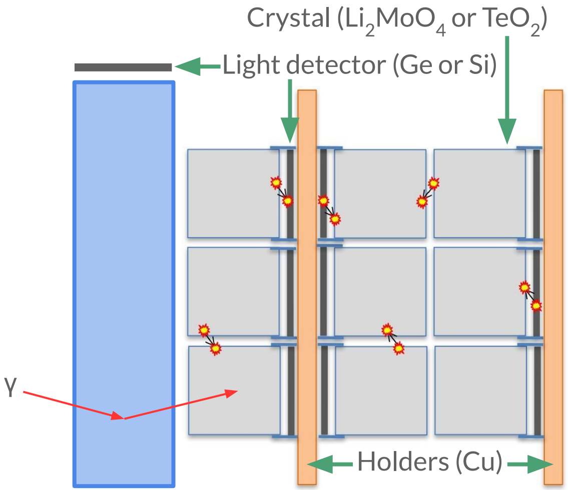
- Main idea: the crystals should be surrounded exclusively by active material
  - Light detectors acting as active veto against α and β from detector holder (copper)
  - Active veto against γ's from cryostat
- Detector structure successfully tested
- Active γ veto under advanced characterization
- Dedicated cryostat under commissioning in Modane





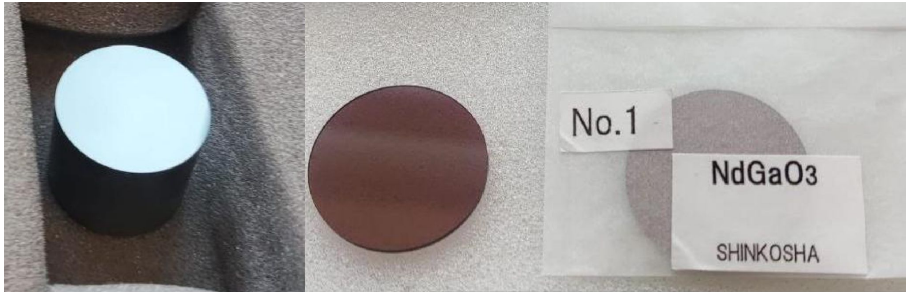






TINY

- Goal: investigate feasibility of bolometric search of 0νββ decay on:
  - ^{76}Zr with ZrO_2 scintillating crystals using NTD readout
  - ^{150}Nd with $NdGaO_3$ crystals using high-impedance NbSi TES
    →Particle discrimination via pulse shape on TES
- TINY proof-of-concept
  - Natural crystals to demonstrate detector technology
  - Already competitive wrt NEMO-3
- TINY-baseline
  - 5 × 400g $^{76}ZrO_2$ crystals
  - 5 × 400g $^{150}NdGaO_3$ crystals
  - Background goal: 10^{-3} counts/keV/kg/yr



How do we go even further?

- Event topology
  - Discriminate bulk vs surface events by further developing CROSS technology
  - Discriminate single-site $\beta\beta$ events from e.g. multi-Compton γ events with e.g. athermal phonon sensors
- Energy resolution
  - Understand mechanism that dominates energy resolution in bolometers
- Precision measurements with multi-isotope approach
  - R&D on new crystals is fundamental to validate any future evidence of $0\nu\beta\beta$ decay
  - Developing an effective enrichment technique for ^{48}Ca could be pivotal for precision measurements